

Experimental Analysis of Proton-Induced Displacement and Ionization Damage Using Gate-Controlled Lateral PNP Bipolar Transistors

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Abstract- The electrical characteristics of proton-irradiated bipolar transistors are affected by ionization damage to the insulating oxide and displacement damage to the semiconductor bulk. While both types of damage degrade the transistor, it is important to understand the mechanisms individually and to be able to analyze them separately. In this paper, a method for analyzing the effects of ionization and displacement damage using gate-controlled lateral PNP bipolar junction transistors is described. This technique allows the effects of oxide charge, surface recombination velocity, and bulk traps to be measured independently.

I. INTRODUCTION

Exposure to high-energy photons (e.g., x-rays) has been shown to give good estimates of the TID damage caused by protons in MOS devices [1]. This is because bulk displacement in MOS devices has little effect on device performance since the active region of a MOS transistor is at the surface and MOSFETs are majority-carrier devices. However, photon sources give very little insight into the effects of displacement damage in a bipolar transistor (BJT). Energetic particles (protons) create much more displacement damage than photons. Exposure to these particles creates vacancies and interstitial atoms in the semiconductor lattice [1]. These defects introduce traps that reduce the lifetime of free carriers in the semiconductor bulk, thereby increasing the recombination rate and base current in BJTs. Increased base current in a bipolar transistor is the primary cause of radiation-induced current gain degradation.

The lateral PNP (LPNP) bipolar junction transistor (BJT) is the device under study. The LPNP transistors have an active base region at the Si/SiO₂ interface between the emitter and collector and the current flow in this device is laterally between these two junctions, just beneath the oxide. This area is the area where recombination centers occur. Thus, ionizing radiation will degrade lateral transistors more significantly than vertical transistors [2].

In this summary, a gate-biasing technique is described that allows the effects of ionization- and displacement-induced defects to be measured independently. Using gate-biased transistors, the bulk lifetime parameter (τ), the surface recombination velocity (sr_v), and oxide trapped charge (N_{ot}) can be found, independently from each other. Experimental results from both proton and x-ray irradiated lateral gated

PNP transistors are presented to provide a qualitative introduction to this technique.

II. DEVICES AND EXPERIMENTAL DETAILS

The gate-controlled lateral pnp transistors (GCLPNP) studied in this paper were manufactured by VTC in their Whisper1 process (a BiCMOS process) [3]. A representational cross-section of the device is shown in Figure 1. As shown, an independent gate terminal is between the emitter and collector, above the active base region. The emitter is annular with a diameter of 1.8 μ m and a junction depth of 0.45 μ m, the active base width is 2.6 μ m, and the base oxide thickness is 370 nm. The p-type emitter doping concentration at the surface is 10^{20} cm⁻³ and the concentration of the n-type epi layer forming the base region is 3×10^{16} cm⁻³.

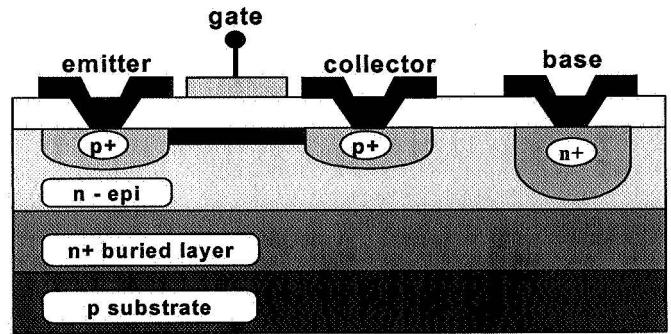


Fig.1 Representational cross-section of LPNP with the gate terminal deposited over the active base region [10].

Test devices were subjected to either of two sources of irradiation. The first set of parts were exposed to 200-MeV protons at the Indiana University Cyclotron Facility (IUCF) at a fluence level of 8.5×10^{12} cm⁻². The particle flux was 5.0×10^9 cm⁻²s⁻¹. The second set of parts was irradiated in an ARACOR 10 keV x-ray source at Vanderbilt University at a dose rate of 250 rad(SiO₂)/s. The total dose on these parts is 500 krad(SiO₂). During both the proton and x-ray irradiations, the parts were exposed with all leads shorted and grounded. The HP 4156 parameter analyzer was used to take pre- and post-irradiation measurements.

These radiation levels were chosen in order to correlate the damage caused by proton and x-ray irradiations. Proton damage can be correlated to the x-ray damage by

converting the proton fluence to units of total ionizing dose [4,5]. It has been shown that 10 keV x-rays can effectively reproduce the ionization damage caused by 200-MeV protons

$$EquivalentTotalDose = \frac{\Phi_p}{1.7 \times 10^7}$$

[4,5] by using a conversion factor of $1.7 \times 10^7 \text{ cm}^{-2}$. For example, $1.7 \times 10^{12} \text{ cm}^{-2}$ protons (200-MeV) are needed to deposit one rad in SiO_2 [5]. Equation 1 gives:

In this proton irradiation test case, $8.5 \times 10^{12} \text{ cm}^{-2}$ 200-MeV protons were used to deposit approximately 500 krad(SiO_2) onto the test chip, which is equivalent to the total dose provided by the x-ray irradiation.

III. EXPERIMENTAL RESULTS

Excess base current, ΔI_b , is typically selected as the parametric indicator of both total dose and displacement damage[6,7]. Figure 2 shows the excess base current for the GCLPNP for equivalent doses of proton and x-ray irradiation. Here data were measured with the collector-base and gate-base biases maintained at -1.5V and 0V respectively with emitter-base voltage swept from 0.4V to 0.8V. The figure shows the degradation in the transistor due to irradiation by an increase in excess base current, which was expected. The figure also shows that when both ionization and displacement damage are present (i.e., proton damage), degradation is greater than when only ionization damage is present (i.e., x-ray damage). This is most likely due to bulk displacement, which is characteristic of proton damage [1].

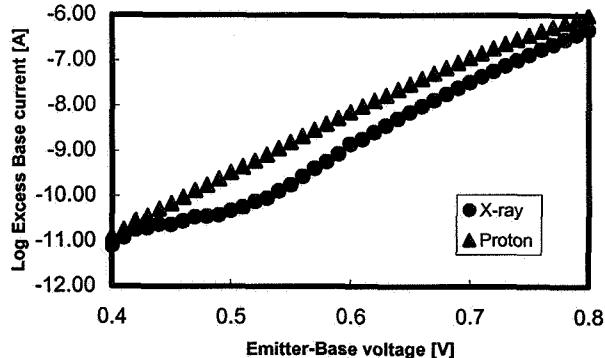


Fig.2 Excess base current in GCLPNP devices for equivalent doses of proton and x-ray irradiation.

Further data was taken with the same devices so that separation of the ionization damage from the bulk displacement would be possible. In these measurements, the emitter-base bias is maintained at 0.6V, the collector-base bias is still maintained at -1.5V and the gate-base voltage swept from 20V to -60V. The pre- and post-rad data are shown in Figure 3. This data set is showing the base current versus applied gate voltage. At positive gate bias, the transistor is in accumulation. Accumulation occurs when electrons are collected at the surface of the n-type base. As the gate bias approaches negative values, the transistor moves into

depletion, and ultimately into inversion, where electrons are pushed into the bulk of the base.

The results in Fig.3 indicate that displacement damage (proton irradiation) is indeed more destructive than ionization (x-ray) damage. Although the pre-rad curves exhibit similar characteristics, the post-rad curves differ from each other, as well as from the pre-rad curves by a large margin. The increase in base current while the lateral PNP is in accumulation is a direct result of a change in the lifetimes of the carriers in the silicon bulk. The peak of each curve represents the maximum probability that carriers at the surface will recombine. According to Shockley-Read-Hall recombination statistics, this maximum recombination occurs when the concentrations of holes and electrons are balanced, or when the gate voltage moves the intrinsic energy at the interface so that it lies equi-distant between the carrier quasi-Fermi levels [6]. This energy level is also known as the midgap voltage (V_{mg}) [6]. From this peak, the changes in oxide charge and the surface recombination velocities can be determined, which is shown in the Analysis section of this paper.

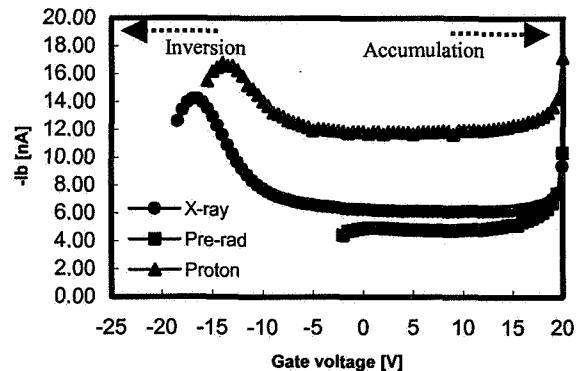


Fig. 3. Pre- and post-irradiation base current measured with respect to the applied gate bias. Note that pre-rad data showed similar characteristics between parts.

IV. ANALYSIS

In bipolar devices, ionization effects are primarily related to the generation of net positive oxide trapped charges and to the increase in surface recombination velocity (srV) which is due to the formation of interface traps [2]. The excess interface traps lead to a change in base current by increasing carrier recombination in the base. Displacement damage causes the generation of traps in the bulk which lead to a decreased carrier lifetime. Using the gate-biasing technique described above, each of these electrical effects can be determined separately, showing that proton irradiation does indeed create more displacement damage than x-ray irradiation.

A. Bulk lifetime

The bulk lifetime is the lifetime of minority carriers in the base region, and it is denoted by the bulk lifetime parameter, τ . Displacement damage results in an increase in bulk traps, which corresponds to an decrease in τ . As the

lifetime decreases, recombination occurs more rapidly causing an increase in base current. These relationships are given by:

$$\tau = \frac{qA_E n_i^2 x_B}{2N_d I_B} \left[e^{\left(\frac{qV_{EB}}{kT} \right)} - 1 \right]$$

[8] and,

$$\Delta\tau = \tau_{\text{prerad}} - \tau_{\text{postrad}} \quad (3)$$

where τ is the minority carrier lifetime in the bulk, I_B is the minimum base current in accumulation, A_E is the surface area of the annular emitter, x_B is the width of the active base region, N_d is the doping of the bulk, and V_{EB} is the forward bias at the emitter-base junction. See Table 1 at the end of this section for numerical results.

B. Surface recombination velocity

Increased surface recombination velocity (sr_v) is a result of ionization-induced interface traps in the active base region of the GCLPNP. The recombination velocity can be approximated by [6,7]:

$$\Delta sr_v = \frac{2\Delta I_{B\text{peak}}}{qS_{\text{peak}} n_i e^{\left(\frac{qV_{EB}}{2kT} \right)}} \quad (4)$$

where S_{peak} is the surface area over which peak recombination takes place [6,7]. $\Delta I_{B\text{peak}}$ is a measure of how much the base current changed from pre- to post-rad. Note that this is not the difference between peak values of base current, but rather, it is the difference between $\Delta I_{B\text{pre-rad}}$ and $\Delta I_{B\text{post-rad}}$. $\Delta I_{B\text{peak}}$, and subsequently, Δsr_v can easily be determined numerically using the above equation and the pre- and post-rad gate swept data for the device. Figure 4 shows the physical references of these data points. See Table 1 at the end of this section for numerical results.

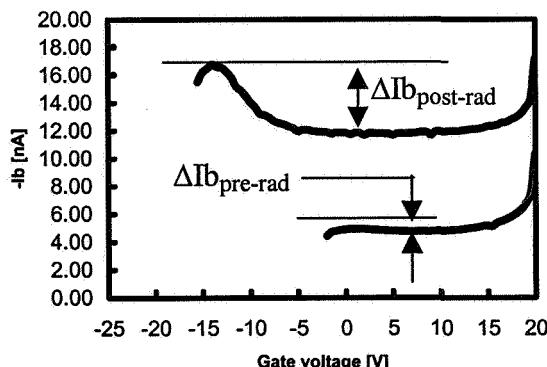


Fig. 4. Peak and minimum values of base current for both pre- and post-rad measurements for the proton irradiation.

C. Positive oxide trapped charge

In lateral transistors, large densities of N_{ot} affect the free carrier concentration of the active base, moving it toward inversion. An increase in N_{ot} indicates a buildup of positive oxide charge, typically an effect of ionization damage. Figure 5 shows the large shift in the free carrier profiles near the surface for the proton radiation data, this is seen at the midgap voltage. Similar results can be seen for the x-ray radiation data.

The radiation induced positive oxide trapped charge will scale directly to the shift in midgap voltage [9]. For a given total dose, the increase in the sheet charge is:

$$\Delta N_{ot} = \Delta V_{mg} C_{ox} q^{-1} \quad (5)$$

with C_{ox} being the capacitance of the oxide and V_{mg} being the gate voltage at which recombination is maximum (the peak value of base current). The midgap voltages associated with these data sets are indicated in Figure 5. See Table 1 at the end of this section for numerical results.

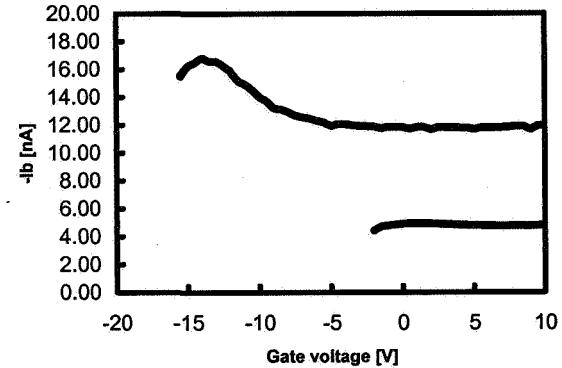


Fig. 5. Gate voltage at peak recombination sites for proton data.

Table 1
Numerical Results for GCLPNP

	X-ray	Proton
Δsr_v (cm/s)	260	170
ΔN_{ot} (cm ⁻²)	10×10^{11}	9×10^{11}
$\Delta\tau$ (s)	2×10^{-11}	2.5×10^{-9}

V. DISCUSSION

The gate controlled LPNP's under study in this paper were irradiated using equivalent amounts of proton and x-ray total dose. In theory, applying equal amounts of radiation to a transistor should incur approximate equal amounts of damage to the transistor. This results in a study of the types of radiation being used. X-ray's are high energy photons while protons are very energetic and have a much larger mass. These large energetic particles have the ability to cause damage to an atomic lattice, while the photons would not.

This is known as displacement damage, or the generation of bulk traps.

Using the gate biasing technique, the electrical effects from both types of radiation were able to be separated and measured independently. Bulk lifetimes are found by studying the base current when the transistor is in accumulation. Accumulation is when the majority carrier concentrations are higher at the surface of the base than they are in the bulk. This condition leads to a decreased minority carrier lifetime in the bulk, and an increased base current. Table 1 shows the numerical values found for these data sets. The minority carrier lifetimes in the proton irradiated part were shortened by 2.5 ns. Since each carrier has a shorter lifetime, it must be recombining at a faster rate. Current is dependent on time, and as more carriers recombine, the base current is driven higher, degrading the gain of the transistor. A small change in lifetime is seen in the x-ray data, but shortening the lifetime of the minority carriers by 0.02 ns has a very small effect on the recombining base current. Thus, x-ray's do not seem to cause bulk traps, while proton's do.

After taking the displacement damage into account, the ionizing degradation due to both types of irradiation was approximately equal. Using the gate-swept responded, ΔN_{ot} and ΔN_{ot} were also able to be measured independently and the consistent degradation trends resulting from ionization damage can be seen.

VI. CONCLUSION

The proton radiation response of bipolar junction transistors is complicated by its sensitivity to both ionization and displacement effects. Using a gate-biasing technique, ionization and displacement effects have been separated and analyzed independently. In order to substantiate these results, x-ray irradiations were performed on the same devices. It was shown that ionization damage was consistent between both types of irradiations, and that the displacement damage occurred only in the proton irradiated parts. This damage complemented the fact that excess base current in the proton damaged parts was higher than in the x-ray damaged parts. The separation of ionization and displacement damage using a gated bias is a technique that may allow proton damage to be estimated through the independent measurements of radiation damage.

VII. REFERENCES

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